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L.F. AND M.F. PROPAGATION: sky-wave field-strength prediction

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Summary

During the night, medium-frequency sky-waves propagate to great distances via the ionosphere. The report describes the various factors which affect the waves as they travel from transmitter to receiver. Several methods which can be used for estimating the strength of sky-wave signals are compared.

issued under the authority of

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Research Department, Engineering Division,
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L.F. AND M.F. PROPAGATION: SKY-WAVE FIELD-STRENGTH PREDICTION

P. Knight, M.A., Ph.D., M.I.E.E.

1. Introduction

This report is based on a lecture which was given at the three seminars organised by the International Telecommunications Union prior to the 1974 Frequency-Planning Conference. The purpose of the seminars was frequency planning to engineers who would be attending the 1974 Conference. Since the lecture was mainly concerned with field strength prediction, the various propagation curves and prediction methods which are available for planning are considered in detail. To assist in the better understanding of the differences which arise when waves propagate at various latitudes or in different directions, the factors which influence the strength of medium frequency sky waves are discussed. The diurnal, short-period and solar-cycle variations of signal strength which arise in practice are also described.

2. Field strength variation

2.1 Diurnal variation

During the day, l.f. and m.f. sky-waves are absorbed by the ionosphere and are unable to propagate further. After sunset, however, the D region of the ionosphere, which absorbs the waves during the day, decays rapidly, and waves are then reflected with little loss from the higher E and F layers. Multi-hop propagation to great distances is the possible.

Fig. 1 shows how sky-wave field-strengths increase after sunset on most paths. The signal-strength increases by about 20 dB in the two hours centred on sunset and then remains more steady. At sunrise the D region ionisation is re-established and the signal-strength decreases rapidly*.

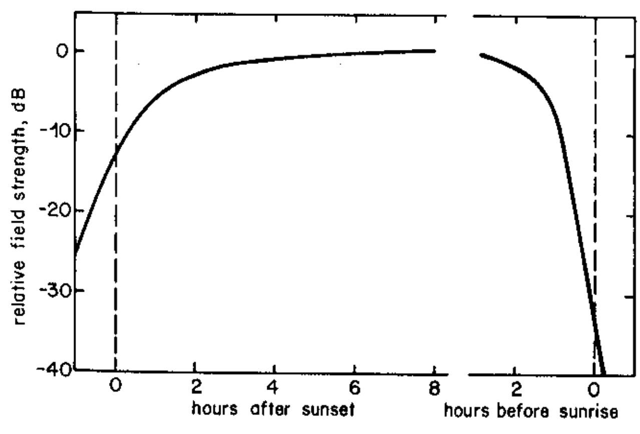

Fig. 1 - Field-strength variation during the night and at sunrise

At l.f. and m.f., propagation to great distances always takes place via the E-layer, about 100 km above the ground. Although reflections from the somewhat higher F-layer are possible on shorter paths at the higher frequencies in the m.f. band, E-layer reflections usually predominate.

2.2 Short-period and day-to-day variation

Because the ionosphere is a turbulent medium, the strength of sky-wave signals varies continually, the rate of variation depending on frequency and path length. At frequencies below 1 MHz, several minutes may elapse between consecutive maxima. On higher frequencies, however, several maxima may occur during one minute, especially on shorter paths where E and F-layer reflections are present simultaneously. If a continuous recording is made for half an hour, the field-strength exceeded for 10% of the time (the quasi-maximum field-strength) will be found to be about 5 dB greater than the field-strength exceeded for 50% of the time (the median value).

If recordings are made for half-hour periods at the same time after sunset on a series of nights, the median value will be found to vary considerably from night to night. The median field-strength exceeded on 50% of the nights is the measured value usually quoted, and is also the value derived from propagation curves and prediction formulae. The median field-strength exceeded on 10% of the nights, however, is between 5 and 10 dB greater than the stated value. Because of the combined effect of short-period and day-to-day variations, the field-strength exceeded for 10% of the total time on a series of nights will be between 7 and 11 dB higher than the overall median value usually stated. For planning purposes it is reasonable to assume that the field-strength exceeded for 10% of the time is 10 dB greater than the overall median.

Because of this day-to-day variation, measurements made on only one or two nights cannot be regarded as reliable. If the interference caused by a particular transmitter is to be evaluated, measurements must be made on a sufficient number of nights for the overall median value to be accurately determined.

2.3 Solar-cycle variation

An additional source of variation is caused by solar activity, field strengths being lower at the peak of the solar cycle. In Europe the decrease at m.f. is found to be

*Fig. 1 shows field-strength variation in terms of the times at which the sun sets and rises at the ground below the ionospheric reflection point. On multi-hop paths the diurnal variation is controlled by the reflection point where the sun sets last or rises first.

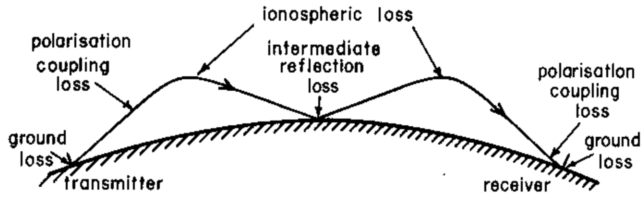

Fig. 2 - Losses on a two-hop path

approximately $Rd \times 10^{-5}$ dB, where R is the sunspot number (typically 150 at the peak of the solar cycle) and d is the path length in km[1]. In North America the decrease is much greater but in tropical regions it may be smaller. At l.f. there appears to be little or no variation. The field-strength decrease should be disregarded for planning purposes, because co-channel interference will be worse when solar activity is least ($R = 0$).

3. Factors which influence sky-wave field-strength

As the wave propagates from transmitter to receiver it is subject to a number of different types of loss which are illustrated in Fig. 2. These losses are considered in detail in this section.

3.1 Ground loss at transmitter and receiver

Propagation curves such as those published by the CCIR usually apply to paths whose terminals are well inland. They therefore take account of the ground loss due to imperfect ground conductivity which occurs at transmitter and receiver[2,3]. Greater field-strengths will be observed, however, if either the transmitter or receiver is situated near the sea, provided the first (or last) part of the path lies over the sea. This increase occurs because sea water is a better conductor than land and reflects waves more efficiently, especially at the low angles which are important for long-distance propagation.

Fig. 3 shows the approximate increase which would occur at m.f. if ground of average conductivity (10 mS/m) were replaced by sea water at either the transmitter or receiver; the increase will be doubled if both are near the sea. The increase rises to a maximum when the path length is about 2000 km, because here the one-hop mode predominates and is propagated at a very low angle. The increase rises to a further maximum at about 4000 km; here the 2-hop mode predominates. For paths longer than 6000 km the increase may be assumed to be 10 dB when one terminal is near the sea or 20 dB if both are close to the sea. Similar increases occur at l.f.

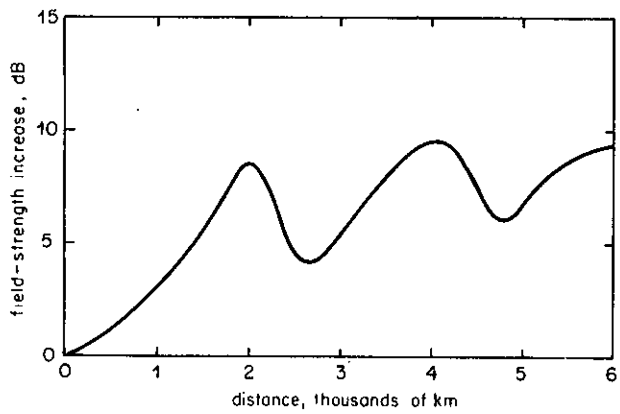

Fig. 3 - Effect of replacing land, at transmitter or receiver, by sea

The full increase shown in Fig. 3 will only apply if the transmitter or receiver is within a few km of the sea. Fig. 4 shows how the field-strength depends on the actual distance from the sea (measured in the direction of propagation) when one terminal of a 1500 km path is moved inland, assuming ground of average conductivity (10 mS/m) and a frequency of 1 MHz.

3.2 Polarisation coupling loss

Conventional aerials radiate vertically-polarised waves. At m.f. the wave which is accepted by the ionosphere and which propagates further, usually has a different polarisation and may not be excited efficiently by the incident wave. The wave which emerges from the ionosphere is in general elliptically polarised and may not excite the listener's receiving aerial efficiently, because aerials near the ground are most sensitive to vertical polarisation.

The fraction of the incident power which is lost on entry into the ionosphere is called the polarisation coupling loss[4]. Further polarisation coupling loss occurs when the wave which emerges from the ionosphere induces a voltage in the receiving aerial. The coupling losses which occur at the two ends of the path are caused by essentially the same mechanism and are unchanged if the direction of propagation is reversed.

Polarisation coupling loss is caused by the Earth's magnetic field and therefore depends both on magnetic-dip angle and on the direction of propagation relative to magnetic north, as shown in Fig. 5. The major axis of the elliptically-polarised wave which is accepted by the ionosphere, and also that of wave which emerges, is parallel to the direction of the Earth's magnetic field. Consequently

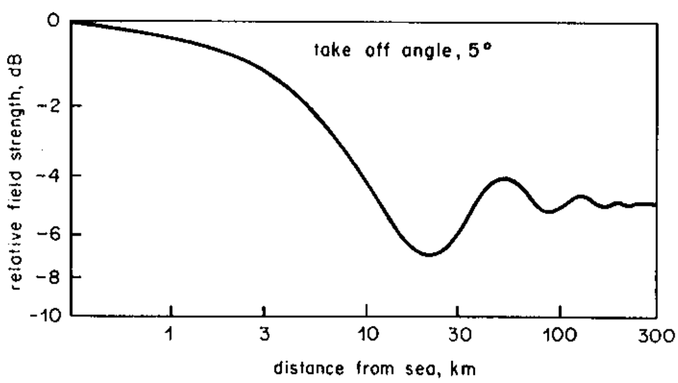

Fig. 4 - Variation of field strength with distance from sea

polarisation coupling losses are low in temperate latitudes, because the Earth's magnetic field is almost vertical. At the magnetic equator, however, the Earth's field is horizontal and polarisation coupling losses on East-West paths are large.

Polarisation coupling loss does not occur outside the m.f. band because it is a consequence of the gyromagnetic frequency, which falls within the m.f. band*. The gyromagnetic frequency depends on the strength of the Earth's magnetic field, and varies from 1·5 MHz in temperate latitudes to 0·7 MHz in some parts of the equatorial region.

3.3 Ionospheric loss

As mentioned in Section 2.1, sky-wave field-strengths increase after sunset because ionospheric losses decrease. Late at night the field-strength reaches its greatest value but some residual ionospheric loss remains. The residual loss on a long path may be considerable and it is therefore an important factor which must be taken into account.

It can be shown theoretically that ionospheric loss is least when the direction of propagation is parallel to the direction of the Earth's magnetic field. In equatorial regions, therefore, ionospheric losses for low-angle modes on north-south paths are smaller than on east-west paths, as shown in Fig. 6. Since east-west propagation at all latitudes is perpendicular to the direction of the Earth's field, losses on East-West paths are independent of latitude outside the auroral zone.

*The gyromagnetic frequency is the frequency with which electrons in motion spiral around the Earth's magnetic field lines. If the sense of rotation of an elliptically-polarised wave of similar frequency is such that it enhances this motion, power drawn from the wave will be transferred to the electrons and the wave will be rapidly attenuated. If the wave has the opposite sense of rotation, however, it will propagate with little attenuation.

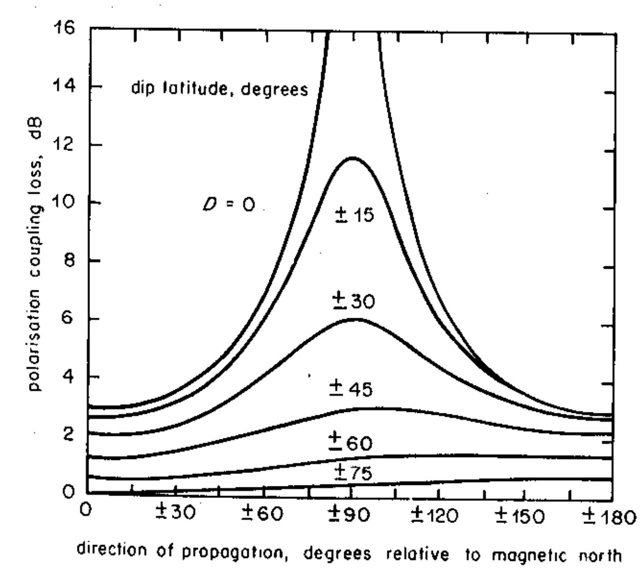

Fig. 5 - Polarisation coupling loss

Although the rate of attenuation in the ionosphere decreases with increasing frequency, waves of higher frequencies penetrate more deeply into the ionosphere and the distance traversed within the ionosphere is greater than at lower frequencies. Consequently the variation of the total loss with frequency is much smaller than would otherwise be the case. Fig. 6 shows that ionospheric loss is, in fact, almost independent of frequency within the m.f. band on north-south equatorial paths.

In the auroral zones, ionospheric losses are somewhat greater than those shown in Fig. 6. The auroral zones are centred on the magnetic poles and have an outer radius of about 4000 km. Areas which are affected by increased losses include Canada and the northern USA, the North Atlantic and the northern part of the USSR. In this region, ionospheric losses are independent of the direction of propagation because the Earth's magnetic field is almost vertical.

3.4 Intermediate reflection loss

Fig. 7 illustrates the reflection of a wave at the Earth's surface on a multi-hop path. When the wave is reflected its strength is reduced because of losses in the ground, and its polarisation is also modified. The polarisation of the reflected wave may differ from that required by the ionosphere on the next hop and polarisation coupling loss, similar to that described in Section 3.2., will occur at m.f. The sum of the ground reflection loss and the polarisation coupling loss is known as intermediate reflection loss[4,5]. It depends on a complicated way on the direction of propagation, on the direction of the Earth's magnetic field and on the ground constants at the reflection point.

There are three situations in which the loss may be large:

1. In temperate latitudes when the down coming wave is reflected from land at an angle near the Brewster angle. The loss may depend on the direction of propagation, waves propagating towards the west suffering most loss.

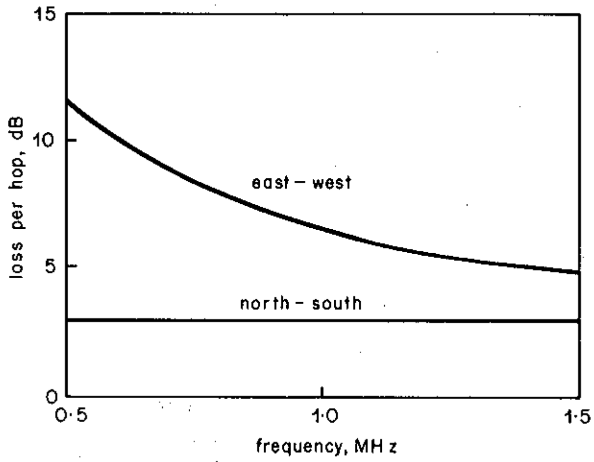

Fig. 6 - Ionospheric loss at the magnetic equator

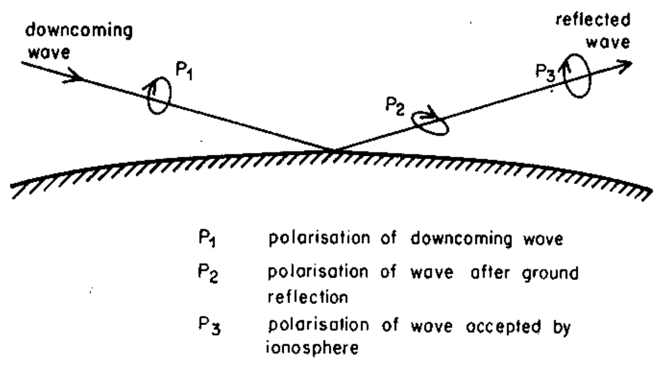

Fig. 7 - Intermediate reflection loss

2. For east-west propagation with sea reflection at 45° dip latitude.

3. For north-south propagation with sea reflection at the magnetic equator.

At l.f. only the ground reflection loss need be considered, and this is usually small.

4. Sky-wave field-strength prediction

For planning purposes, some method is required for estimating sky-wave field-strength. Possibilities range from the detailed calculation of all the losses described in Section 3, to the use of propagation curves derived from measurements.

At extensive series of measurements over paths between Europe and North America, and over paths between North and South America, was made between 1934 and 1937. The two sets of measurements were used to produce separate curves for east-west and north-south propagation, shown in Fig. 8; these curves were agreed at the Cairo Conference in 1938. The curves shown in Fig. 8 are in fact 9 dB lower than the original Cairo curves because the latter give quasi-maximum values; the curves shown in Fig. 8 therefore represent median field-strengths when I kW is radiated from a short vertical aerial.

A further series of measurements was organised within Europe by the EBU between 1952 and 1960. The resulting propagation curves, also shown in Fig. 8, were adopted by the CCIR as Report 264, with a recommendation that they be used in the European Broadcasting Area. Other curves contained in Report 264 give corrections for the greater ionospheric loss near the auroral zone, and for the vertical radiation patterns and gains of typical transmitting aerials.

The CCIR curves apply to distances between 300 and 3500 km. Measurements made in Europe at shorter distances show that the maximum field-strength which is likely to be observed during the night may be calculated by assuming that the ionosphere has a reflection coefficient of −10 dB at m.f. and −15 dB at l.f., at the high angles of incidence corresponding to short-distance propagation. Two curves for m.f. calculated on this basis are included in Fig. 8. One curve applies to a short vertical aerial radiating 1 kW; the corresponding curve for l.f. would be 5 dB lower. The other curve applies to a hypothetical semi-isotropic source producing the same field-strength, in all directions, as that produced by the short vertical aerial in the horizontal direction. Similar curves for a semi-isotropic source calculated on the same basis, which extend the CCIR curves to distances less than 300 km, are given in Fig. 8 of CCIR Report 431[7]; slightly different extensions were used at the African Broadcasting Conference. Although a semi-isotropic source cannot be realised in practice it forms a convenient reference, especially when field-strengths at very short distances, due to high angle radiation, are being calculated.

At distances greater than 300 km it is immaterial whether the source is a short vertical aerial, a semi-isotropic source or a vertical aerial up to 0·25 λ high. If the transmitting aerial is higher than 0·25 λ, or if the aerial has horizontal directivity, the field-strengths given by the curves should be increased by the aerial gain in the direction of interest; the resulting field-strength then corresponds to the expected value when 1 kW is radiated.

Fig. 8 shows that there are certain discrepancies between the three sets of curves and the question which arises is: which curves should be used? For planning purposes, curves representative of average conditions are the most convenient; corrections such as those shown in Figs. 3 and 5 can then be applied in special circumstances.

For distances less than 300 km, in temperate latitudes, propagation curves calculated by assuming that the ionosphere has reflection coefficients of −10 dB at m.f. and −15 dB at l.f. give reasonable estimates of the highest median field-strengths which are likely to be observed, and are therefore useful for predicting maximum interference levels. If the curves are used for planning a sky-wave broadcasting service, however, account should be taken of the fact that field strengths may, at times, be consid-

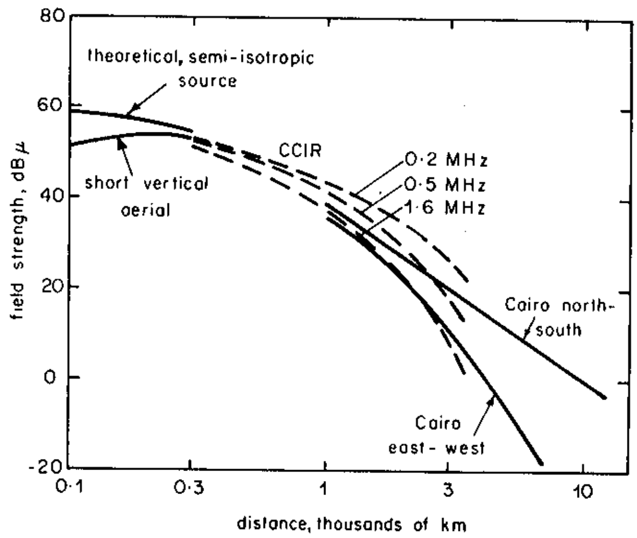

Fig. 8 - Propagation curves

erably less than the values given by the propagation curves. Field-strengths may be up to 20 dB lower if the wave is about to penetrate the E-layer, or about 6 dB lower if it is reflected from the F-layer.

The CCIR curves apply to distances between 300 and 3500 km and were derived from measurements made within this range. There is no justification for extrapolating them to greater distances, and it has been shown that serious errors result if this is done[7]. The variation of field-strength with frequency shown by the CCIR curves is now thought to be too great; it is possible that the variation with frequency is unimportant, at least within the m.f. band.

The Cairo curves were derived entirely from measurements made at m.f. and there is therefore no justification for using them for l.f., although they may not be seriously in error at l.f. No dependence on frequency within the m.f. band was observed. The north-south curve may not represent average conditions because one of the terminals used for the measurements was situated near the sea; a more representative north-south curve would perhaps be 10 dB lower. The east-west curve does not represent average conditions either because all the paths measured were across the North Atlantic and were close to the auroral zone. More recent measurements suggest that the difference between north-south and east-west paths, away from the auroral zone, is much less than the Cairo curves indicate.

The problem of producing simplified propagation curves or formulae valid for all distances is being actively pursued by the CCIR. One possibility, which has been proposed by the USSR[9] and which is being studied further, is the derivation from measurements of a formula in the following form:

$$E = \underbrace{115 - 20\log_{10} d}_{\text{unattenuated field-strength}} \quad \underbrace{-\,T}_{\text{terminal losses}} \quad \underbrace{-\,kd}_{\text{path attenuation}}$$

where E is the field-strength in dB relative to 1 μV/m and d is the distance in km via the ionosphere, approximately equal to the path length for distances greater than 1000 km. The terminal loss T would be of the order of 10 dB except on east-west paths near the magnetic equator, where polarisation coupling loss is large. The constant k will probably be a function of geomagnetic latitude, direction of propagation, frequency and sunspot number. Corrections of the form shown in Fig. 3 would then be applied if the transmitter or receiver is situated near the sea.

Another possibility would be the use of the wave-hop method[5] developed by the BBC. In this method all the losses which arise as the wave propagates from transmitter to receiver are calculated separately and are subtracted from the unattenuated field-strength. The calculation is performed for all the propagation modes which are likely to contribute to the received signal; if two or more modes are found to be of comparable strength, their powers are added. Although the wave-hop method is laborious to use in its present form, its adaptation to a digital computer is thought to be feasible. For the time being its use should be confined to paths which are outside the range of validity of propagation curves or formulae, or where their accuracy is doubtful.

One situation where propagation curves would not be expected to apply arises when horizontal transmitting aerials are used for short-distance broadcasting via the ionosphere. Although radiation at the low angles corresponding to long-distance propagation is greatly reduced, waves can propagate to considerable distances by high-angle multi-hop modes, which are strongly excited. Recent EBU measurements of a particular horizontally-polarised transmission have shown that these modes can in fact produce field-strengths comparable with those due to a vertical aerial radiating the same power, and this has been confirmed by wave-hop calculations.

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